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Seismic hazard mapping in Gorakhpur, India: A multi parametric approach using predominant frequency, amplification and engineering bed rock depth

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ABSTRACT

Gorakhpur city, situated in the Indo-Gangetic Plain of northern India and classified under Seismic Zone IV, is increasingly getting vulnerable to earthquake-induced ground motion due to its proximity to active Himalayan belt, growing urban footprint and soft alluvial subsurface conditions. This study presents a comprehensive seismic hazard assessment based on key site parameters, including average shear wave velocity up to 30 m ($Vs30$), predominant frequency (f_0), fundamental time period (T_0), peak amplification (A_0), engineering bed rock depth (EBR) and the Seismic vulnerability index (Kg). Ambient noise data is used to estimate f_0 and A_0, while shear wave velocity profiles were obtained through study of Multichannel Analysis of Surface Waves (MASW). Spatial interpolation and GIS-based mapping of these parameters, reveal significant heterogeneity in the subsurface response characteristics. Zones with low $Vs30$, low f_0, longer T_0, high EBR, high A_0 and high Kg values, primarily in the southern parts of the city, demonstrating a high potential for ground motion amplification and structural resonance. The Kg index, effectively highlights the most seismically vulnerable zones within the city, while EBR is estimated using predominant frequency and shear wave velocity. The results underline the critical need for microzonation-based land use planning, earthquake-resilient construction, and site-specific design codes. This study provides essential input for seismic risk reduction and sustainable urban development in Gorakhpur, and establishes a framework for similar assessments in other seismically active regions of the Indo-Gangetic basin.

Keywords: Seismic hazard; $Vs30$; Predominant frequency; Seismic vulnerability index; Engineering bed rock; Gorakhpur; Indo-Gangetic Plain

INTRODUCTION

Earthquakes remain one of the most catastrophic natural hazards, capable of causing extensive loss of life, infrastructure damage, and economic disruption (Kanamori, 1977; Bilham, 2009). The destructive potential of an earthquake is not solely governed by its magnitude or epicentral distance, but also by local site conditions**,** which can significantly amplify ground motions (Seed et al., 1976; Borcherdt, 1994). Hence Seismic hazard assessment is a foundational component of earthquake risk mitigation and resilient urban planning, particularly in tectonically sensitive, thick alluvial subsurface and densely populated regions where seismic ground motions is significantly influenced by local site conditions (Wang and Takada, 2005). While the magnitude and distance of an earthquake source are primary contributors to ground motion intensity, local site effects governed by the subsurface geological and geotechnical conditions, play a crucial role in modifying seismic waveforms. These effects can significantly amplify or de-amplify the ground shaking, affecting the safety and performance of infrastructure during seismic events (Borcherdt, 1994; Bard, 1999). Hence, the characterization of site parameters such as average shear wave velocity ($Vs30$), predominant frequency (f_0), fundamental period (T_0), peak ground amplification (A_0), engineering bed rock depth (EBR) and the seismic vulnerability index (Kg), has emerged as an essential part of site-specific seismic hazard evaluation and microzonation (Nakamura, 1989; Lermo and Chávez-García, 1993; Ibs-von Seht and Wohlenberg, 1999; Delgado et al., 2000).

Gorakhpur City, located in the eastern part of Uttar Pradesh in the Indo-Gangetic Plain, lies in Seismic Zone IV as per the BIS (1893) Part 1 classification, indicating a high damage risk zone. With a population exceeding 0.67 million and a rapid urban growth rate (Census of India, 2011), Gorakhpur's vulnerability to earthquakes is further compounded by its dense infrastructure and ongoing expansion. Its proximity to active Himalayan faults and the alluvial nature of its subsurface deposits enhances the seismic vulnerability of the region (Mohanty et al., 2007; Kolathayar and Sitharam, 2012). In light of growing urbanization and infrastructure development, especially post-2015 urban expansions, it becomes imperative to assess the site response characteristics of the city using various geophysical techniques.

Several studies have emphasized the importance of site characterization for seismic hazard mapping. Nakamura (1989, 2000) introduced the Horizontal-to-Vertical Spectral Ratio (HVSR) technique to estimate predominant site frequency, which has since become a standard method in microtremor-based studies and has been used in recent scenarios as well, such as Shankar et al. (2021a) and Singhania et al. (2026) . Lermo and Chávez-García (1993) validated the use of HVSR in urban site response assessment using single-station measurements. Delgado et al. (2000) introduced the Kg index as an empirical indicator of seismic vulnerability, integrating both amplification and frequency components. Anbazhagan et al. (2010) estimated engineering bedrock depth for shear wave velocity 760 m/s and the depth to bedrock can be estimated using the empirical relation $H = V_s/4f_0$, which is based on the fundamental resonance condition of shear waves in a soil layer overlying the bedrock (Nakamura, 1989; Ibs-von Seht and Wohlenberg, 1999).

In the Indian context, Sitharam et al. (2013) conducted a local site assessment for Lucknow city, while Anbazhagan et al.

(2010) carried out a similar study for Bangalore. Nath et al. (2019), Shankar et al. (2021a), Tiwari et al. (2024) and Shekhar et al. (2025), performed local seismic site characterization in Varanasi, highlighting the spatial variability of f_0 and $Vs30$ in the Ganga alluvial belt. Similarly, studies by Bajaj and Anbazhagan (2019) in the Indo-Gangetic basin and Sitharam et al. (2013) in Uttar Pradesh revealed high amplification zones in regions dominated by thick alluvium. Shankar et al. (2021b) and Khan et al. (2025) also investigated local site parameter for Gorakhpur city. However, Gorakhpur remains largely understudied in terms of integrated, site-specific seismic hazard mapping using dynamic geophysical parameters, despite its strategic and seismic significance.

In this study, the primary objective is to conduct a detailed site-specific seismic hazard assessment of this city by utilizing-site response parameters derived from both field-based geophysical measurements and secondary datasets. Specifically, the study aims to assess the seismotectonic framework to understand the regional seismic setting of Gorakhpur and its surroundings; estimate and spatially interpolate the $Vs30$ using multichannel analysis of surface waves (MASW) and existing borehole data; and derive the predominant frequency (f_0) and corresponding T_0 through microtremor (ambient noise) measurements and HVSR analysis. Additionally, we computed peak ground amplification (A_0) and generated amplification maps for seismic zoning, evaluated the Seismic Vulnerability Index to identify areas with higher potential for seismic damage, and performed EBR modelling. Together, these integrated approaches are intended to provide a robust, high-resolution site-specific seismic hazard profile of Gorakhpur city, supporting effective earthquake risk mitigation and informed urban planning in this region.

STUDY AREA

Gorakhpur city is situated in the eastern part of Uttar Pradesh in India, within the Indo-Gangetic Plain (GDA, 2025). The study area covers both the municipal limits and the peri-urban expansion zones as delineated in the Proposed Land Use Map under Gorakhpur Master Plan 2031 (Revised) (Figure 1). The city is geographically positioned between 26°40′N–26°50′N and 83°20′E–83°30′E, with a total area covered by the Gorakhpur Development Authority (GDA) under which the Gorakhpur Master Plan 2031 is being implemented, has expanded to 643 sq. km. This expanded area includes the Gorakhpur Municipal Corporation, three Nagar Panchayats (Pipraich, Pipiganj, Munderwa Bazar), and 319 villages (GDA, 2024)

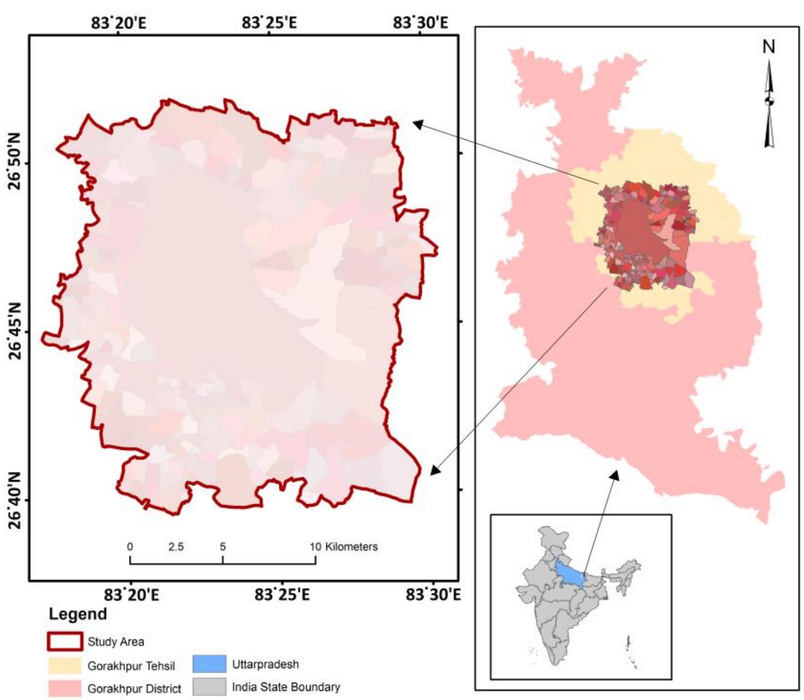

Figure 1. Study area map of Gorakhpur adopted from Gorakhpur Revised Master Plan 2031

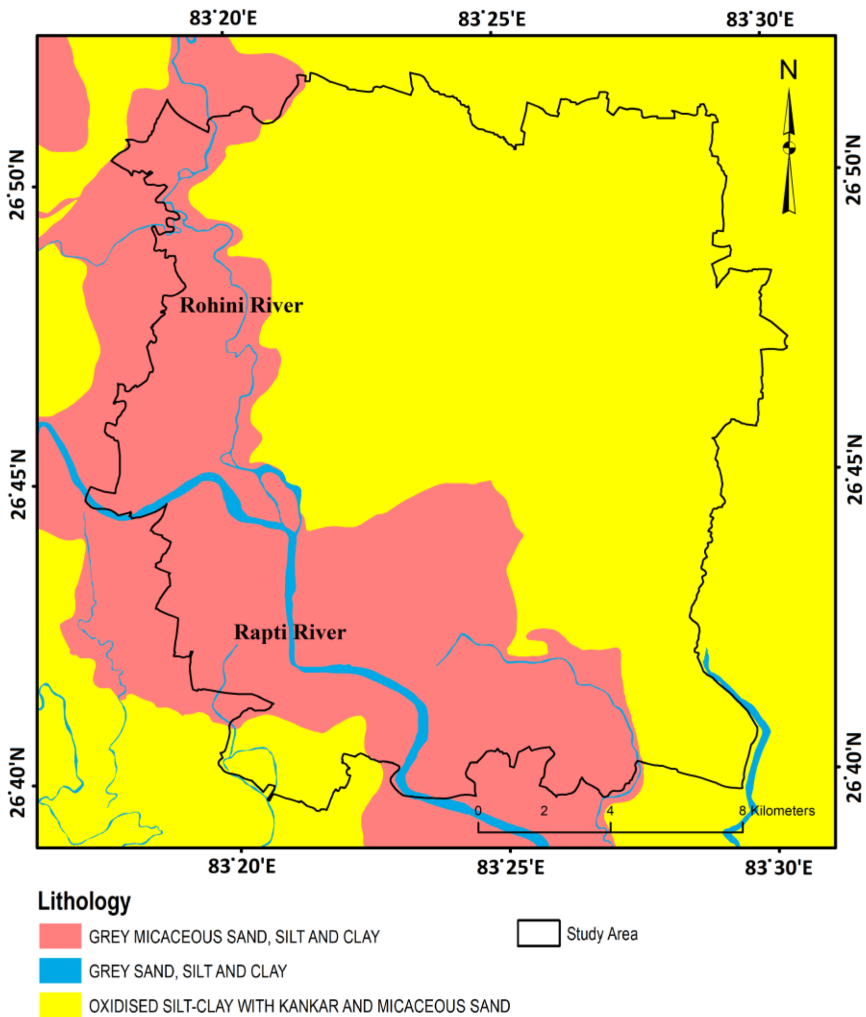

Figure 2. Geological map of Gorakhpur showing the major stratigraphic units (Source: Bhukosh-GSI, 2024)

GEOLOGY AND GEOMORPHOLOGY

The region's geology is characterized by alluvial deposits accumulated over millions of years due to the erosional and depositional activities of Himalayan River systems (Figure 2) (GSI, 2018). The area's geological profile consists primarily of Quaternary sediments, overlying older Tertiary deposits. These sediments are mainly alluvial, comprising sand, silt, and clay in varying proportions.

The geological structure can be divided into three main units: the topmost layer of Recent to Sub-recent alluvium, consisting of fine sand, silt, and clay, typically 10-20 meters thick; the underlying older alluvium, composed of coarser materials including sand, gravel, and occasional clay lenses, extending to depths of 150-200 meters. The Siwalik Group forms the basement rock, consisting of sandstone, shale, and conglomerate of Mio-Pliocene age. (Valdiya, 2010; Singh et al., 2015; Bonsor et al., 2017).

Geomorphologically, Gorakhpur city lies on a flat alluvial plain with a gentle north-south slope, bounded by the Rapti and the Rohini rivers (Figure 3). These rivers have significantly influenced the local landscape through their meandering courses and periodic flooding. The area's geomorphological features include active floodplains along the rivers, older floodplains less prone to flooding, river terraces formed by river incision, and abandoned channels filled with finer sediments (GSI, 2020). These geological and geomorphological characteristics play a crucial role in determining the distribution of shear wave velocities and engineering bedrock depths across the city, which are central to this study's objectives (Sinha and Friend, 1994; Ibs-von Seht and Wohlenberg, 1999).

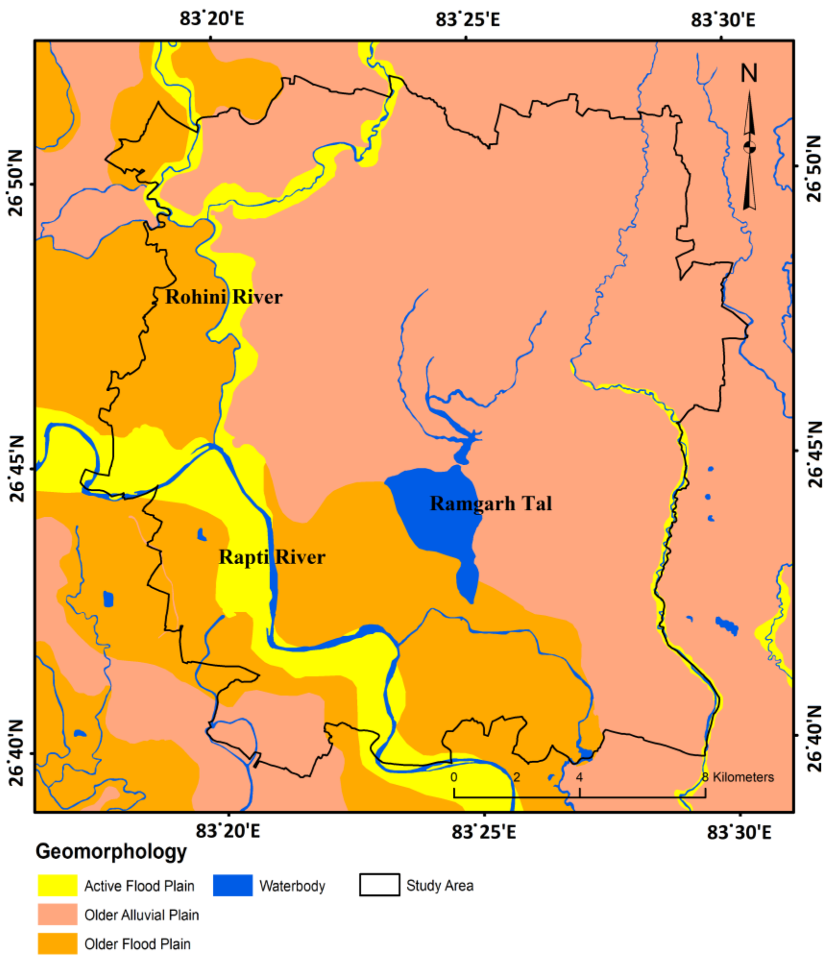

Figure 3. Geomorphological map of Gorakhpur city and its surroundings (Source: Bhukosh-GSI, 2024)

SEISMICITY AND SEISMOTECTONICS

Gorakhpur is located in a seismically active region, influenced by its proximity to the Himalayan collision zone. The city falls under Seismic Zone IV according to the Indian Standard Seismic Zoning Map (BIS, 1893), indicating high damage risk potential. The seismicity of the region is primarily controlled by three major tectonic elements: the Main Boundary Thrust (MBT) located approximately 150 km north, the Himalayan Frontal Thrust (HFT) about 80-100 km north, and the East Patna Fault running NE-SW about 150 km southeast of Gorakhpur (Seeber and Armbruster,1984; Bilham, 2009; Mukhopadhyay, 2018; GSI, 2018, 2020). Historical seismicity records show that Gorakhpur has experienced significant earthquakes, including the 1934 Bihar-Nepal Earthquake (Mw 8.0), the 1988 Bihar Earthquake (Mw 6.6), and the 2015 Gorkha Earthquake (Mw 7.8) in Nepal, which was felt in Gorakhpur and raised concerns about the city's seismic vulnerability (Bilham, 2004, 2009; NDMA, 2010; Nath and Thingbaijam, 2012; USGS, 2024; ISC, 2024). The seismo-tectonic setting is governed by the presence of several lineaments and buried faults in the Indo-Gangetic Plain (Figure 4).

These features, although not always expressed at the surface, can influence local seismic wave propagation and site response characteristics. The thick alluvial cover in the region can significantly amplify seismic waves, making it essential to accurately characterize the subsurface through Vs and EBR modelling. This seismotectonic context underscores the importance of detailed site characterization studies in the Gorakhpur city. The Vs and EBR models developed in this study will provide crucial inputs for site-specific seismic hazard assessments and help in developing appropriate earthquake-resilient design strategies for the city's infrastructure, addressing the critical need for improved seismic risk mitigation in this rapidly growing urban center. (BIS, 1893; Nath et al., 2007).

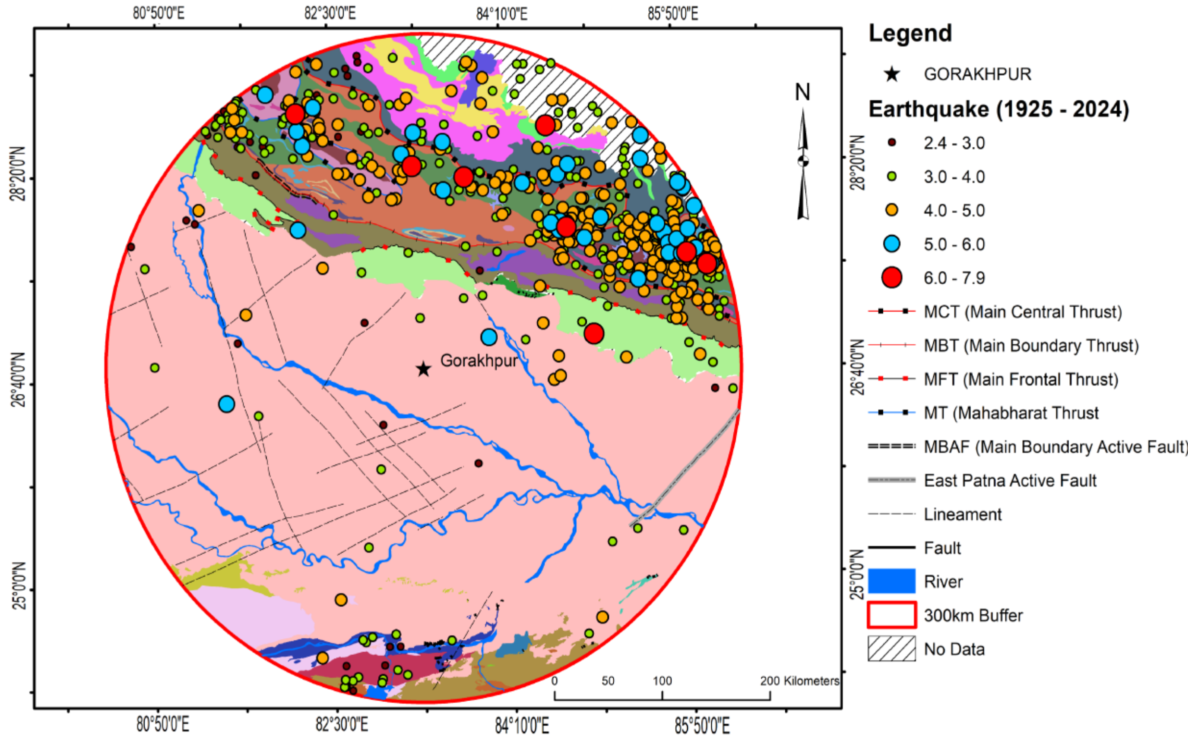

Figure 4. Seismotectonic map of North India showing major faults and historical earthquakes around 300 km of Gorakhpur study area. *(*Source: Bhukosh-GSI, 2024*;* ISC, 2024)

DATA AND METHODOLOGY

Data Sources

This study utilizes a comprehensive collection of high-resolution geophysical and geotechnical datasets to assess the subsurface conditions of Gorakhpur city. The primary data were sourced from the Bhukosh portal of the Geological Survey of India (GSI), which provides access to detailed geospatial, and subsurface information, which are essential for seismic hazard assessment (Bhukosh-GSI, 2024). Key datasets include MASW profiles and microtremor survey records. MASW profiles, acquired by Geological Survey of India (GSI) at multiple strategic locations across Gorakhpur, supply shear wave velocity (Vs) measurements that are fundamental for evaluating subsurface stiffness, stratigraphy, and identifying engineering bedrock (Park et al., 1999; GSI, 2020). Complementing this, microtremor surveys were conducted in accordance with the HVSR methodology to estimate the fundamental frequency (f_0) of local soil columns, a critical parameter for site response analysis (Nakamura, 1989; SESAME, 2004). These surveys were implemented as part of GSI's ongoing seismic microzonation initiative, which aims to delineate zones of varied seismic amplification and vulnerability within urban centres (GSI, 2020). Spatial and urban planning data, including the Gorakhpur Master Plan 2031 (Revised), boundary delineations, and land-use information, were incorporated based on resources provided by the Gorakhpur Development Authority (GDA). These documents ensure that the study's spatial framework reflects both current urban extents and anticipated expansions (GDA, 2025). Additional reports and supporting datasets were consulted from the Uttar Pradesh Avas Evam Vikas Parishad (UPAVP), GDA, and other local governmental agencies to enrich the analysis with demographic, infrastructural, and developmental context. The integration of MASW and microtremor f_0 datasets form the foundation for evaluating engineering bedrock depth and dynamic site response characteristics. This multi-source data approach enables a robust assessment of seismic vulnerability and enhances the geotechnical understanding of Gorakhpur's subsurface, supporting informed urban planning and disaster resilience strategies.

Methodology

The methodology employed in this study integrates various geophysical, geotechnical and geospatial techniques to develop comprehensive seismic hazard model for Gorakhpur city. Our approach began with collection of existing geological, geophysical, seismological, geotechnical and geospatial data from various sources, including government agencies and previous studies (Park et al., 1999; GSI, 2020). We then collected data for the city, through series of field investigations carried out by the government agencies employing MASW and Microtremor Array Measurements (MAM) to obtain high-resolution Vs profiles. MASW profiles, collected using a 24-channel seismograph with 4.5 Hz geophones, allow for the non-invasive characterization of near-surface stratigraphy and stiffness (Park et al., 1999; Xia et al., 1999). MAM surveys employed broadband seismometers arranged in circular arrays of varying diameters to capture both shallow and deep velocity structures (Okada, 2003). These geophysical datasets were complemented by Standard Penetration Test (SPT) data from strategically located boreholes, providing constraints on soil properties and enabling correlation between Vs and SPT-N values (Ohta and Goto, 1978; GSI, 2020). Data processing involved the application of advanced signal processing techniques to extract dispersion curves from both active MASW and passive MAM seismic data. These dispersion curves were then inverted using a neighbourhood algorithm to obtain 1-D Vs profiles at each measurement location (Sambridge, 1999). The inversion process incorporated a priori information from borehole logs and geological maps to constrain the solutions.

$$Vs(30)_{Estimated} = 30/\sum \frac{v_i}{h_i} \tag{1}$$

The point measurements of Vs were then interpolated using geostatistical methods, primarily ordinary kriging, to create continuous spatial models across the study area (Isaaks and Srivastava, 1989). Cross-validation techniques were employed to assess the accuracy of the interpolation and to optimize the kriging parameters. Additionally, we integrated topographic data and surficial geology maps into our analysis to refine the spatial models, particularly in areas with limited direct measurements (GSI, 2020). Finally, we developed a GIS database to store, visualize, and analyze the spatial distribution of Vs and EBR across the city. This methodology allowed us to create robust, high-resolution models of subsurface properties, providing a solid foundation for subsequent seismic hazard and site response analyses in the region.

To assess the site response characteristics of the studied city, a combination of geophysical field investigations and empirical analyses was employed. Ambient noise recordings were carried out at over 50 sites across the city using a three-component seismometer. The HVSR technique, as proposed by Nakamura (1989), was applied to extract predominant frequency (f_0) and amplification factors (A_0) at each location. The fundamental time period (T_0) was calculated as the inverse of predominant frequency (f_0). MASW-derived $Vs30$ values were validated using borehole data wherever available. The Seismic Vulnerability Index (Kg) was computed as,

$$Kg = {A_0}^2/f_0 \tag{2}$$

Where A_0, is the peak ground amplification factor, and f_0 is the predominant frequency of the site, typically obtained through microtremor or H/V spectral ratio analyses, providing a spatial metric of site vulnerability (Delgado et al., 2000). Spatial interpolation and mapping utilized GIS-based Inverse Distance Weighting (IDW), to generate thematic layers for each parameter, supporting the identification of seismic risk zones and the assessment of dynamic site effect variability across the city (Burrough and McDonnell, 1998).

Similarly, the Engineering Bedrock (EBR) depth modelling in this study was performed using microtremor measurements and the established empirical relation between shear wave velocity (Vs), predominant frequency (f_0), and layer thickness. For the purpose of this study, engineering bedrock was defined as the depth where $Vs \geq 760\, m/s$, as per NEHRP classification (BSSC, 2004). Ambient vibration (microtremor) data were recorded at various sites across the study area using a three-component seismometer, and the horizontal-to-vertical (H/V) spectral ratio method (Nakamura, 1989) was applied to determine the site-specific predominant frequency (f_0). This frequency represents the fundamental resonance frequency of the soil column, which is highly sensitive to the shear wave velocity profile and the depth to the underlying stiffer strata. Assuming 1-D vertical propagation of shear waves in a uniform soil layer, EBR depth (h) was computed using,

$$H_{bedrock} = \frac{Vs}{4f_0} \tag{3}$$

where Vs was set to 760 m/s (Nakamura, 1989; Ibs-von Seht and Wohlenberg, 1999).

This formula assumes a 1D vertical propagation of shear waves through a homogeneous soil layer, where Vs represents the average shear wave velocity from the surface to the bedrock, and fo is the site's predominant frequency obtained from HVSR analysis. This approach provides a first-order estimate of seismic bedrock depth. The estimated EBR values were then spatially interpolated using Inverse Distance Weighting (IDW) in a GIS environment to produce a continuous bedrock depth model across the study area, aiding in the assessment of subsurface impedance contrasts critical for seismic site response.

RESULTS AND DISCUSSION

Average shear wave velocity up to 30 m ($Vs30$)

The spatial distribution of $Vs30$ across Gorakhpur city reveals significant heterogeneity in subsurface stiffness. $Vs30$ values range from below 220 m/s in soft alluvial zones near riverbeds to over 320 m/s in relatively compacted or urbanized areas with shallow bedrock (Figure 5). According to NEHRP site classifications, much of the city falls under Site Class D (180–360 m/s), indicating a medium-to-high potential for seismic amplification. The lowest $Vs30$ values are concentrated in the southern and south-western parts of the city, which correspond to areas with thick unconsolidated sediments. This highlights the need for reinforced design codes in these regions, especially for mid-rise buildings vulnerable to resonance effects.

Predominant Frequency (fo)

The predominant frequency map derived from HVSR analysis shows a wide variation across the study area, ranging from 1.05 Hz to 9.3 Hz (Figure 6). Low frequency zones ($f_0 \leq 2.0$ Hz) are primarily located in areas with thick soft deposits, indicating a higher likelihood of resonance with multi-storey buildings. Conversely, higher frequency zones ($f_0 \geq 4.0$ Hz) are associated with shallow or stiffer subsurface conditions, posing a threat to low-rise structures. The observed spatial pattern of f_0 aligns well with the $Vs30$ map, reaffirming the site classification results. These frequency zones help identify critical building height ranges susceptible to resonance and guide appropriate seismic design measures.

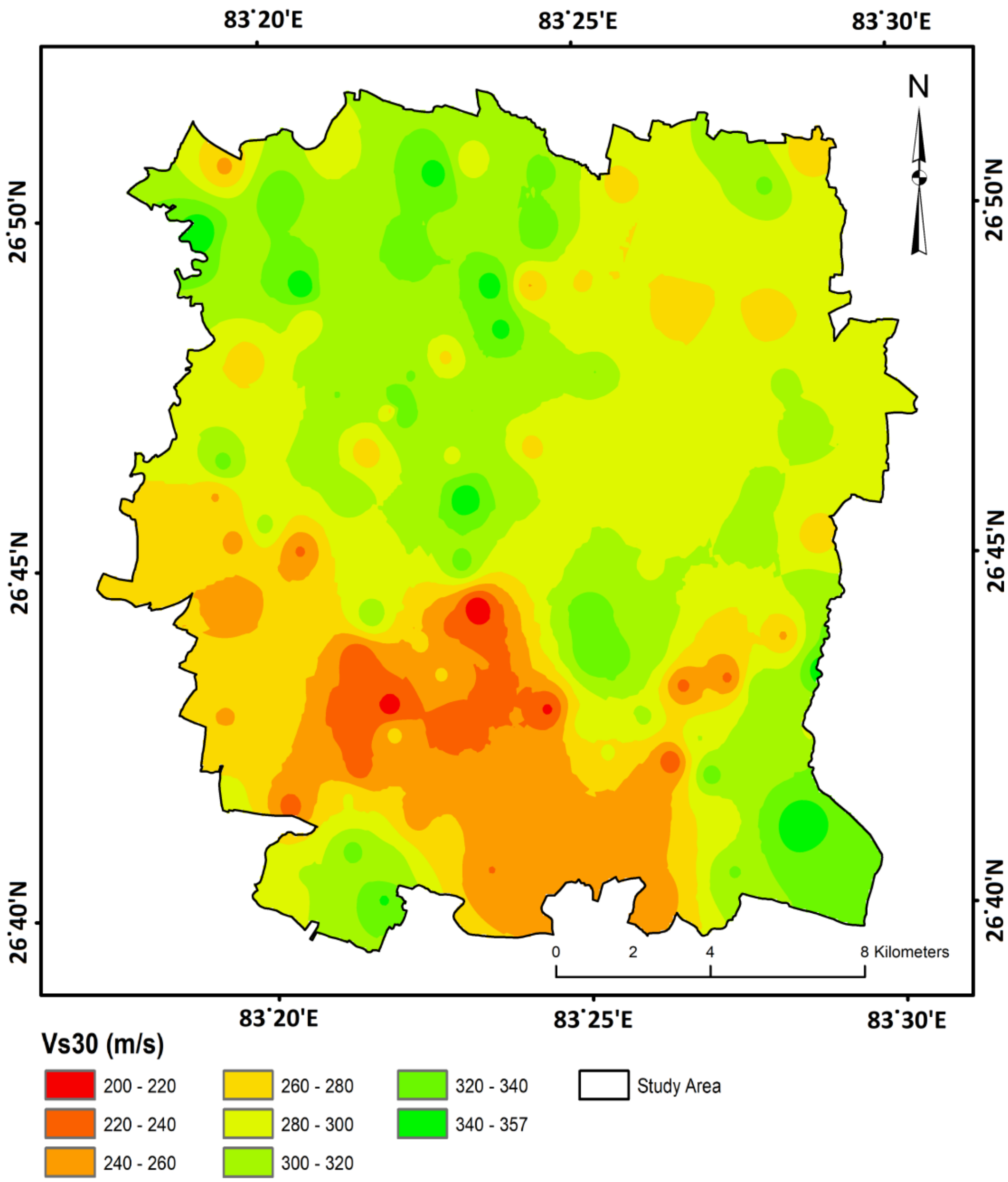

Figure 5. Average shear wave velocity (Vs30) map of Gorakhpur study Area

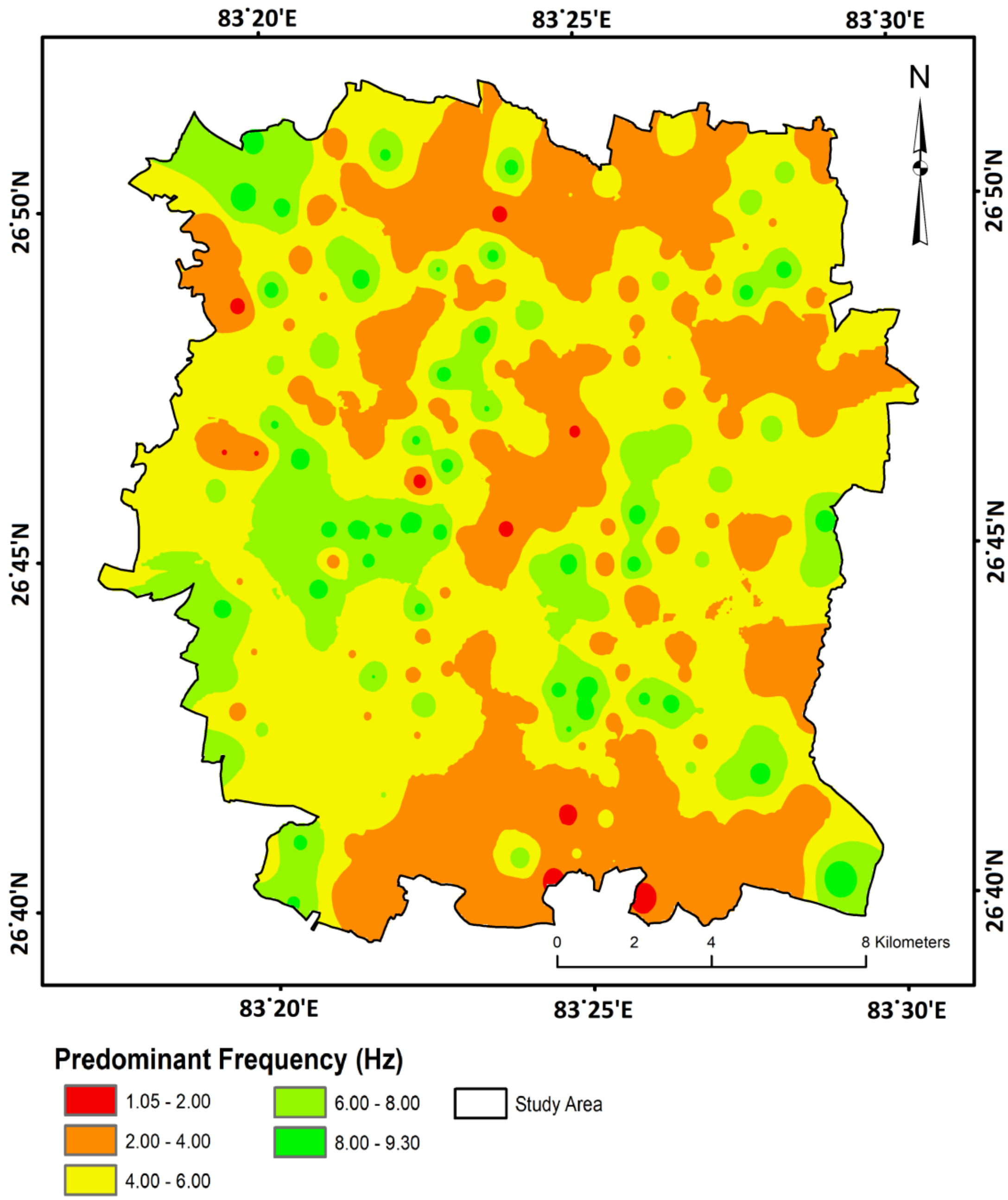

Figure 6. Predominant frequency (fo) Map of Gorakhpur study area

Fundamental time period (To)

The fundamental time period, inversely related to the predominant frequency, varies from 0.13 s to 1 s (Figure 7). Areas with longer periods (>0.6 s) correspond to soft-soil conditions and are particularly hazardous for buildings with similar structural natural periods, such as 4- to 10-storey RC frame structures. Shorter T_0 values (<0.4 s) are found in zones with stiffer soil or shallow bedrock. These periods provide important inputs for seismic code applications and for matching building resonance frequencies with local ground response. The T_0 map thus helps in aligning seismic design strategies with structural vulnerabilities in the region.

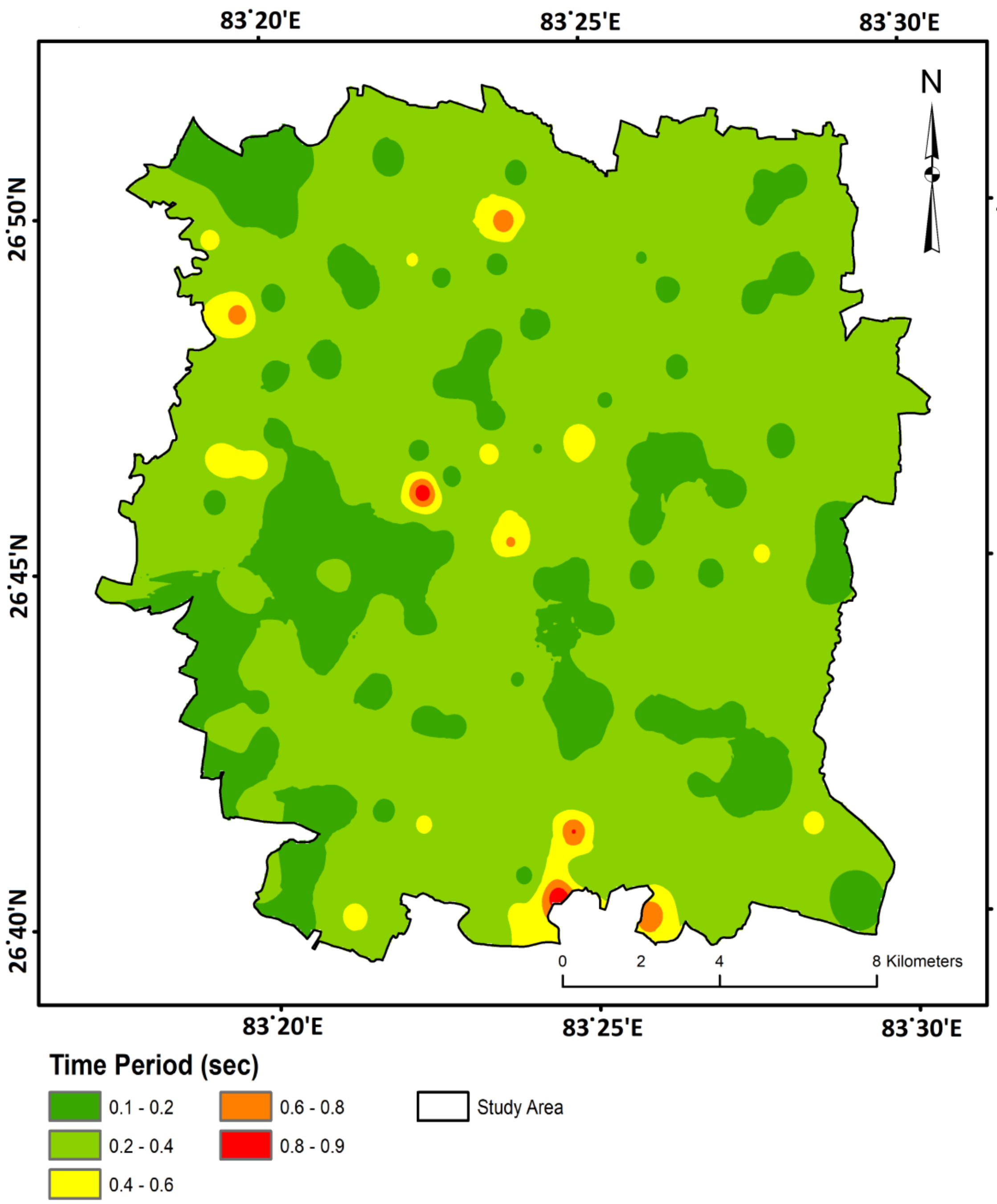

Figure 7. Time period (To) map of Gorakhpur study area

Peak amplification (Ao)

The peak amplification factor A_0, extracted from HVSR spectral ratios, ranges from 0.7 to 3.6, indicating varying degrees of seismic wave amplification due to site effects (Figure 8). High A_0 values are predominantly observed in soft, water-saturated alluvial regions, particularly near floodplains and low-lying terrain. The amplification is typically highest in areas with low $Vs30$ and low f_0, where resonance and wave trapping are prominent. This suggests that even moderate magnitude earthquakes could generate disproportionately high ground motion in these regions. Identification of high-amplification zones is critical for prioritizing retrofitting efforts and updating building codes in these areas.

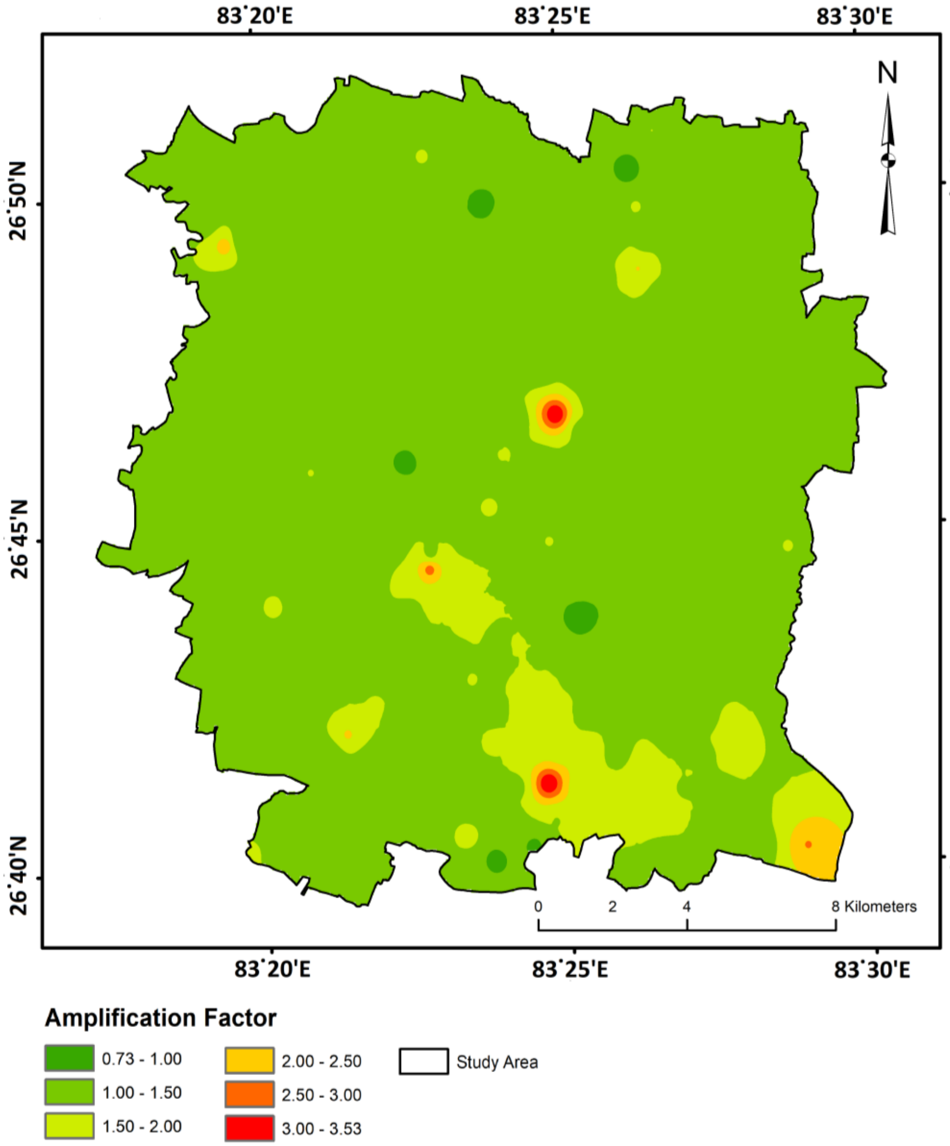

Figure 8. Amplification factor (Ao) map of Gorakhpur study area

Seismic vulnerability index (Kg)

The seismic vulnerability index integrates both the amplification factor and predominant frequency to quantify overall site vulnerability. Kg values in this city range from 0.1 to 10.1**,** with higher values indicating more vulnerable zones (Figure 9). The highest Kg values are recorded in regions with high A_0 and low f_0, suggesting a strong likelihood of resonance with mid-rise buildings and significant ground motion amplification. These zones are primarily located in the distributed parts of the city. The Kg map provides a composite and practical tool for urban seismic risk microzonation, enabling policymakers to identify and mitigate risk in the most vulnerable sectors. This index is widely used empirical parameter to assess site-specific seismic response characteristics, particularly the potential for ground motion amplification due to local soil conditions. Introduced by Nakamura (2000) and further utilized by Delgado et al. (2000), Kg is defined by the equation (2). This index provides a composite measure of seismic vulnerability by capturing both the intensity and frequency characteristics of ground motion. A higher Kg value reflects soft soils with low predominant frequency and high amplification, which are more likely to resonate with typical building frequencies, increasing seismic risk. Conversely, low Kg values represent stiffer ground with lower amplification potential. The Kg index has been effectively applied in seismic microzonation studies across various seismic regions to delineate zones of varying site vulnerability and to support earthquake-resilient urban planning (Nakamura, 2000; Delgado et al., 2000).

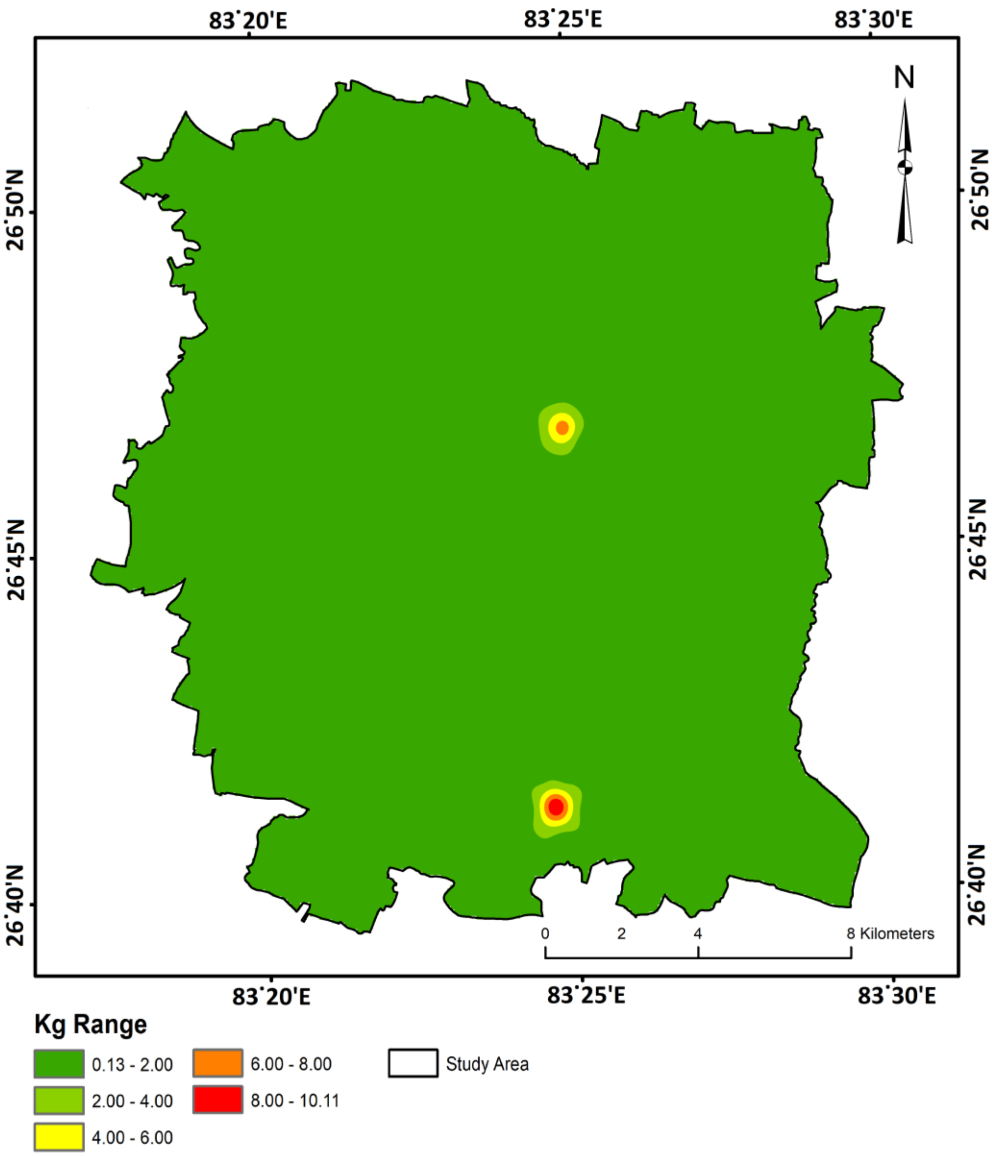

Figure 9. Seismic vulnerability index (Kg) for Gorakhpur study area

EBR modelling

Engineering bedrock is typically defined as the depth at which the shear wave velocity (Vs) reaches or exceeds 760 m/s, marking the transition from softer, unconsolidated sediments to stiffer geological formations that significantly influence seismic wave propagation. In practice, Vs is determined through methods such as MASW, downhole, or borehole geophysical surveys, and these point measurements are often interpolated using geostatistical techniques to generate spatially continuous maps across the study area.

By integrating both Vs and f_0 data, the spatial variation in EBR can be delineated and visualized across the region (Figure 10). For example, in southern areas where f_0 is ≤ 2 Hz and Vs is ≥300 m/s, sedimentary layers are typically thicker, indicating a deeper EBR. Conversely, locations with higher f_0 values of ≥ 4 Hz and lower Vs values of ≤ 260 m/s, suggest shallower bedrock conditions. The EBR in the region varies from 21 m to more than 100 m in some area, reflecting significant subsurface heterogeneity as depicted in the EBR map. Mapping these parameters together provides critical input for seismic microzonation, dynamic site response analysis, and urban infrastructure planning.

This integrated approach not only enhances the understanding of subsurface seismic impedance contrasts which govern the amplification and duration of ground motions during earthquakes, but also supports more informed decisions for engineering design and urban development.

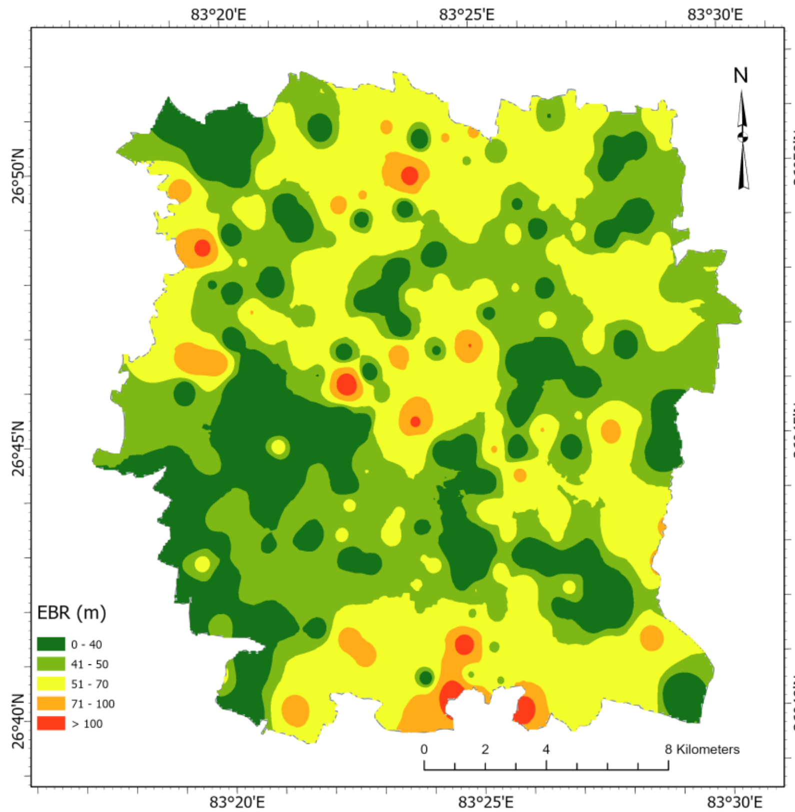

Figure 10. Engineering bedrock (EBR) map of Gorakhpur study area

Seismic hazard

The integrated analysis of dynamic site parameters reveals that the studied city is exposed to varying levels of seismic hazard**,** primarily influenced by local subsurface conditions and geomorphological settings. The spatial distribution of $Vs30$, f_0, T_0, A_0 and Kg collectively delineates the city's seismic response zones. Areas with low $Vs30$ (<260 m/s), low f_0 (<2.0 Hz), long T_0 (>0.6 s), and high A_0 (>2.0), exhibit the highest seismic amplification potential**,** suggesting that even moderate earthquakes could induce intense shaking in these zones. Moreover, the Kg values exceeding 4 in certain regions clearly mark them as highly vulnerable to seismic-induced ground motion and structural resonance effects. These high-risk areas are primarily located in the central urban core and southern zones**,** where thick alluvial deposits, shallow water tables, and unconsolidated sediments dominate. Such geological settings are capable of trapping and amplifying seismic waves, significantly increasing the probability of damage to buildings, especially the mid-rise structures whose natural frequencies coincide with the site's predominant frequency. On the contrary, the western margins, where $Vs30$ and f_0 are relatively higher and Kg values are lower, show comparatively reduced seismic hazard. This spatial differentiation emphasizes the need for microzonation-based seismic planning, including tailored building design, soil improvement, and risk-sensitive land use policies across Gorakhpur City.

Shankar et al. (2021b) conducted study within the Gorakhpur Municipal Cooperation area, and reported $Vs30$ values ranging from approximately 200–360 m/s, f_0 between 0.43 and 1.02 Hz, Ao between 2.55 and 4.81, and Kg between 14 and 55. These values reflect the site conditions of the urban core. Khan et al. (2025) also conducted their study in and around Gorakhpur city, corresponding to these values. In contrast, the present study covers a much wider area, extending to the boundaries defined by the Gorakhpur Master Plan 2031. This expanded coverage reveals a broader range and higher resolution for all parameters. Specifically, $Vs30$ values in the extended area range from below 220 m/s (in the softest, riverine and peri-urban sediments) up to over 300 m/s (in compacted or shallow bedrock regions). The f_0 varies from 1 Hz in thick alluvium to as high as 3 Hz in stiffer soils and outlying regions significantly broader than the municipal-only range. Ao reach up to 3.5 in some low-lying or unconsolidated zones outside the municipal core, and Kg values exceed 10 in several high-risk peripheral areas.

These findings demonstrate that the newly included peri-urban and rural tracts under the Master Plan 2031, exhibit even lower $Vs30$, higher amplification, and broader f_0 ranges than those documented for the city center. As a result, this study provides a more comprehensive and spatially detailed assessment of seismic hazard for Gorakhpur, highlighting the necessity of area-wise microzonation for effective risk assessment and planning.

CONCLUSIONS

This study presents a detailed site-specific seismic hazard assessment of Gorakhpur city including municipal, newly urbanizing and peri-urban area, integrating multiple site parameters derived from various geophysical, geotechnical surveys and empirical analyses. The use of $Vs30$, f_0, To, A_0, and the Kg has provided a multi-dimensional understanding of the city's local site response characteristics. The spatial patterns reveal that the Gorakhpur city is marked by significant heterogeneity in subsurface stiffness and seismic response, with soft-soil zones exhibiting high amplification and long resonance periods, thereby increasing their susceptibility to structural damage during earthquakes. The derived Kg index effectively combines amplification and frequency characteristics, serving as a practical indicator for seismic hazard microzonation and urban seismic risk classification.

The EBR mapping conducted in this study reveals considerable spatial variability in bedrock depth across Gorakhpur, with EBR ranging from 21 m to over 100 m. These highlight the importance of incorporating detailed EBR profiles into seismic microzonation and foundation design, ensuring that local subsurface conditions are adequately represented in seismic hazard assessments. High hazard zones identified through this study require attention in terms of earthquake-resilient building design, infrastructure retrofitting, and urban development regulations. The findings hold valuable implications for policymakers, urban planners, civil engineers, and disaster management authorities. This research also fills a critical knowledge gap, as Gorakhpur has historically been underrepresented in site-specific seismic studies, despite being located in a significant hazardous seismic zone. Future studies may benefit from incorporating 2D and 3D geophysical modelling, nonlinear site response analysis, and probabilistic seismic hazard assessment (PSHA) for deeper insight. Nonetheless, this study lays the groundwork for risk-informed urban planning, promoting long-term resilience in one of eastern Uttar Pradesh's most rapidly developing urban centres.

Acknowledgment

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Author Credit Statement

SS: Conceptualization, data collection and analysis, manuscript review and editing; AT: Conceptualization, data curation, manuscript writing, GPS: Manuscript writing, JLG: Manuscript review and editing;

Data availability

Data can be made available on a reasonable request.

Compliance with Ethical Standards

The authors declare no conflict of interest and adhere to copyright norms.

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