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

Shashank Shekhar[1], Anurag Tiwari[1*], G P Singh[1] and J L Gautam[2]
[1] Department of Geophysics, Banaras Hindu University, Varanasi-221005, India
[2] National Centre for Seismology, Ministry of Earth Sciences, New Delhi- 110003, India
* Corresponding author: aaanuragt@gmail.com

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.