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Seismic Microzonation of Amaravati region: Exploring Geotechnical Data for Site Response Analysis

Chandra B. Ravi[1], Reddy M. Madhusudhan[2,*], Reddy B. Sudharshan[3], R. Saikumar[4] and Chandra Kumar B. Sarath [5]

[1]Department of Electronics and Communications Engineering, G. Pullaiah College of Engineering and Technology, Kurnool, Andhra Pradesh, India.
[2]Department of Civil Engineering, Institute of Aeronautical Engineering, Dundigal, Hyderabad, Telangana, India.
[3]Department of Civil Engineering, Malla Reddy Engineering College, Hyderabad, Telangana, India.
[4]Department of Arts, K L Deemed to be University, Andhra Pradesh, India.
[5]Department of Civil Engineering, Sandip Institute of Technology and Research Centre, Nasik, India.

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Abstract

Amravati has been designated as the prospective youthful capital of the Indian state of Andhra Pradesh, nestled in the geologically stable southern peninsular region. Following the impactful Bhuj earthquake on 26 January 2001 measuring 7.6 Mw on the Richter scale, which resulted in substantial destruction, there has been a heightened curiosity in seismic microzonation research throughout India, encompassing Andhra Pradesh. This study is specifically cantered on evaluating the seismic activity and microzonation of Amaravati, employing a multifaceted seismic hazard assessment methodology. The exploration encompasses three distinct phases. Firstly, site characterization involves regional geological, geomorphological, and geotechnical analysis. Secondly, local site effects and resonance frequencies are assessed using DEEPSOIL software, providing amplification factors through a one-dimensional linear approach. In the third stage, liquefaction hazard analysis and liquefaction potential index are evaluated using the simplified procedure suggested by Seed and Idriss. Microzonation results are presented through nine themes: which includes geological mapping, geomorphology, geotechnical observations, shear wave velocity distribution, seismotectonic set-up, rock depth, amplification, peak ground acceleration, and liquefaction susceptibility mapping. The thematic mapping divides the Amaravati region into three zones: susceptible, partially susceptible, and not susceptible. This comprehensive study enhances understanding of seismic hazards in the Amaravati capital region, aiding in informed urban planning and disaster mitigation.

Keywords: Amaravati, Seismic microzonation, Seismic hazard assessment, Ground response analysis, and Liquefaction index.

1. Introduction

Microzonation is a vital geological and geophysical assessment process that focuses on understanding the seismic hazard and ground shaking characteristics within a specific region, typically on a local scale. This approach involves analyzing the geological, geotechnical, and seismological factors that influence the behaviour of seismic waves as they propagate through the Earth's crust in a particular area. The need for microzonation studies arises from the fact that seismic ground shaking during an earthquake can vary significantly from one location to another, even within a relatively small geographical area [1]. This variation is due to the complex interplay of factors such as local geological and soil conditions, topography, and the nature of seismic waves. Microzonation studies aim to provide a detailed and accurate understanding of these variations, helping to: Assess seismic risk, inform building codes and regulations, site-specific planning, emergency response planning, insurance and risk assessment, and public awareness and education. In the eastern part of South India and the Bay of Bengal region, new fault reactivations have been observed due to the subduction of the Burma plate towards the Bay of Bengal [2-3]. The tectonic setup of the Indian subcontinent as shown in figure 1.

India has a history of facing significant seismic events, such as 1897 Assam earthquake (M_w=8.7), 1905 Kangra earthquake (M_w=8.6), 1934 Bihar-Nepal earthquake (M_w=8.4), 1950 Assam-Tibet earthquake (M_w=8.7), 1991 Uttarkashi earthquake (M_w=6.5), 1993 Latur earthquake (M_w=6.4), 1997 Jabalpur earthquake (M_w=6.0), 1999 Chamoli earthquake (M_w=6.8), 2001 Bhuj earthquake (M_w=7.6), and 2005 Kashmir earthquake (M_w=7.4)[4]. Additionally, there were localized (near to study area) tremors like the Ongole earthquake of 1967 (M_w=5.4) and the Bhadrachalam earthquake of 1969 (M_w=5.7). The impact of these earthquakes varies from area to area, influenced by local factors like soil types and regional seismic sources. The aftermath of earthquakes, though unavoidable and unpredictable, can be mitigated through proper infrastructure planning facilitated by microzonation studies [4],[5]. Ensuring the seismic safety of structures and underground utilities like manholes, sewage lines, water pipes, electricity lines, and gas pipelines, as well as tunnels, plays a crucial role in reducing earthquake-related hazards [6]. The extent of damage during an earthquake is heavily reliant on regional geology and soil conditions, and even a slight change in geological characteristics can lead to contrasting seismic responses over short distances [7]. Geological, geophysical,

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and geotechnical information holds significant importance in assessing seismic hazards through microzonation [8-11]. Soil liquefaction, a phenomenon causing destructive effects like landslides, lateral spreading, and ground settlement, has been observed for decades, gaining attention after 1964 Niigata and Alaska earthquakes. Seismic microzonation involves analyzing ground motion characteristics and response variations during earthquakes, encompassing site characterization, ground shaking intensity, and liquefaction susceptibility [12]. It subdivides an area into micro zones based on site-seismic response, becoming a widely accepted tool for seismic hazard assessment and risk evaluation [12]. This approach considers both source and site conditions [13-14]. Microzonation studies are also instrumental in enhancing land use management for urbanization and future earthquake risk mitigation.

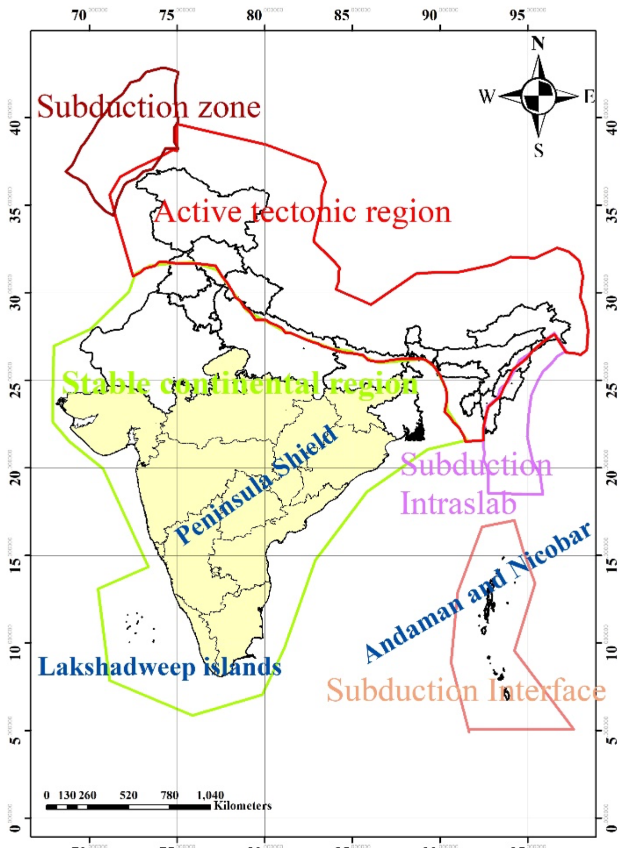


Fig. 1. Tectonic boundaries India and its subcontinent [28]

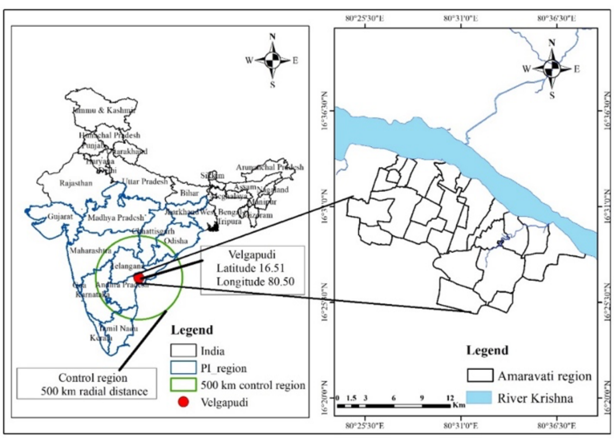


Fig. 2. Geographical location of the Amaravati study region [28]

Following the destructive Gujarat earthquake in 2001, the Indian government placed significant emphasis on seismic microzonation as a guiding framework for safe construction practices and land use planning [15]. This led to microzonation projects in various urban areas, including Delhi, Jabalpur, Chennai, Bangalore, Lucknow, and Ahmedabad, carried out by different researchers [15]. India is divided into four seismic zones based on effective peak ground acceleration (PGA) and the comprehensive intensity scale (CIS-64) [16]. For the current study, the focus is on evaluating seismic hazards for microzonation mapping in Amaravati, the capital of the Andhra Pradesh region. The study area's location map is depicted in figure 2. The study region spans an area of 217.23 sq.km, situated between Guntur and Krishna districts of Andhra Pradesh. The geographical coordinates of the region range from 16°09'80" N to 80°00'9" E in the northwest, 16°01'3" N to 80°01'8" E in the southwest, 16°01'3" N to 81°00'6" E in the southeast, and 16°08'6" N to 80°08'9" E in the northeast.

The objectives of the analysis focus on the Amaravati capital region, which has been recently proposed as the capital of the residual state of Andhra Pradesh. The study is designed around five main steps. Firstly, it aims to establish the geological and geomorphological features of the area to understand its topography better. Secondly, the investigation involves seismic characterization of the capital region by studying historical seismicity and identifying faults present in the area. Thirdly, the analysis aims to evaluate spatial variations in shear wave velocity (Vs_{30}) and predominant frequency for site classification, utilizing data from the standard penetration test (SPT). Additionally, the study seeks to determine ground motion characteristics such as peak ground acceleration (PGA) and ground response spectrum. Lastly, the analysis will identify the liquefaction potential index (LPI) using detailed borehole data and Vs_{30} profiles, applying established methodologies to assess the region's susceptibility to liquefaction. Each of these steps contributes essential information to comprehensively understand the seismic and geotechnical characteristics of the proposed capital region.

2. Methodology

The study utilizes regional factors from the Amaravati area and its surroundings, including geological, historical earthquake, seismotectonic, geotechnical, and groundwater data, to assess seismic hazard. This involves site characterization using Vs_{30} and SPT correlations and ground response spectrum estimates. The methodology follows a detailed step-by-step process outlined in Figure 3. The microzonation mapping corresponds to Level III [17-18], as recommended by the International Society of Soil Mechanics and Foundation Engineering. The procedure includes five stages: characterizing the region, developing a seismotectonic map, estimating seismic hazard parameters, selecting input motion, and performing ground response analysis. Thematic maps are generated using GIS software to represent the outcomes of each stage and develop site-specific design ground motion for Amaravati.

2.1 Evaluation of regional Geography

Assessing the geological, geomorphological, and geotechnical characteristics of an area is a critical step in seismic hazard analysis (SHA). These elements collectively offer crucial insights into the region's vulnerability to seismic activity and the potential impact of earthquakes. Geological factors, such as fault lines and rock types, play a pivotal role in the generation of seismic waves. Meanwhile, geomorphological factors, including topography and landforms, can either amplify or reduce the intensity of shaking. Geotechnical properties of soil and rock layers dictate how ground motion is transmitted, which directly impacts the stability of buildings and infrastructure [19- 20]. A comprehensive understanding of these factors empowers engineers and policymakers to craft effective earthquake preparedness and mitigation strategies, ultimately ensuring the safety of communities and the resilience of infrastructure in earthquake-prone areas [21-24].

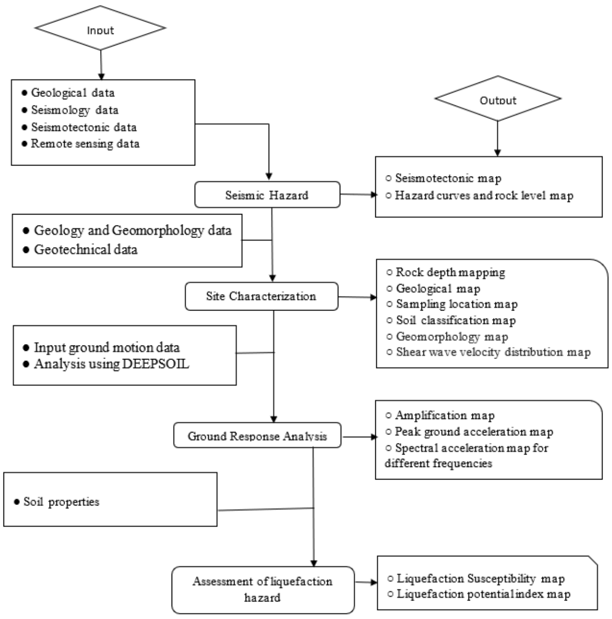
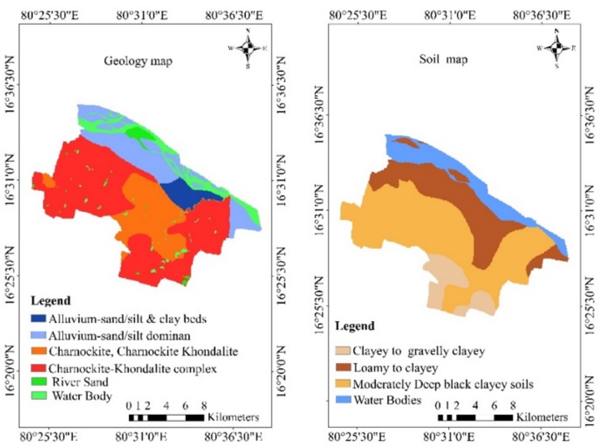


Fig. 3. Methodology adopted for developing the microzonation of Amaravati region [30]

Andhra Pradesh is divided into four main physiographic features: Coastal Plains, Eastern Ghats, Interior Uplands, and Plains. The Amaravati region in Guntur district covers an area of 217.23 km^2 and has diverse lithology including rocks from different age groups. Amaravati region has a long history and is made up of three main groups: Gneisses, Charnockite-Khondalite complex, and alluvium-sand sediments. Charnockite is dominant in the central portion, while the Charnockite-Khodalite complex is more prevalent in the south-southeast and western areas.



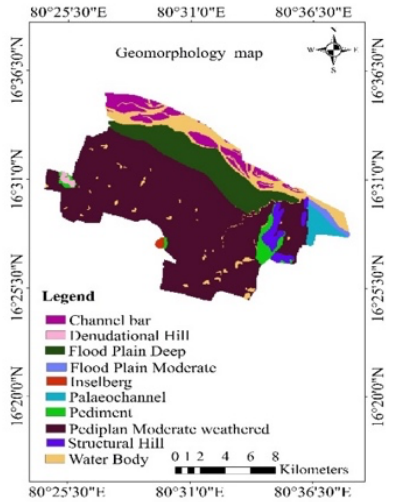


Fig. 4. Geological, geomorphological and soil mapping of the Amaravati region

The Amaravati region is part of the Eastern Ghats and consists of different types of soil such as Charnackites, Khondalites, and Gneisses. The region is characterized by various landforms like the Pedi plain, Alluvial plain, Fluvial, and some marine landforms [25-29]. Geotechnical investigations have been conducted at 65 locations using SPT procedure. Figure 5 displays the map indicating the locations of boreholes, while figure 6 illustrates the corresponding soil profiles, highlighting the maximum depth relative to Vs_{30} and SPT-N variations. Soil samples were collected at different depths and analysed in the laboratory [30-34]. The results showed the presence of various soil types including MH-CH, SC, SC-SM, SM, and SP, as well as weathered rock [35]. Correlations between SPT-N and Vs values were used to determine V_s values for each soil layer, ranging from 139.8 m/s to 486 m/s. The Amaravati region is shallow, with a maximum borehole depth of 46 m. The site was classified as class 'D' and class 'C' according to respectively [36-37]. The estimated Vs values were used in response analysis [38].

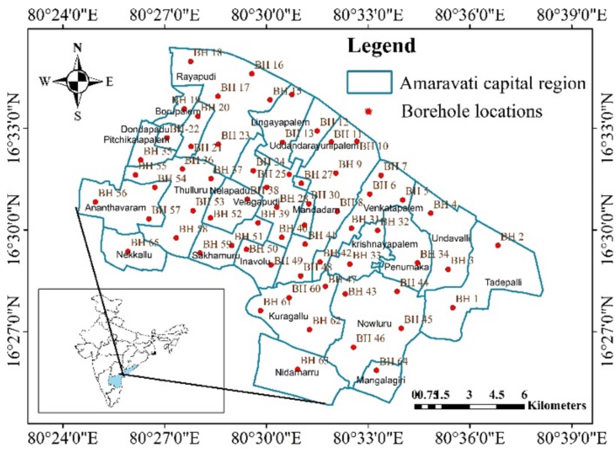


Fig. 5. Borehole location mapping including village boundary.

2.2 Seismicity characteristics of the region

Studying seismicity characteristics in a region is crucial for assessing and mitigating earthquake risks. It allows us to understand the frequency, magnitude, and distribution of earthquakes, which in turn helps in developing effective strategies for earthquake preparedness and response [39]. This knowledge is also instrumental in designing resilient infrastructure, establishing building codes and land-use policies, and reducing the vulnerability of communities to seismic hazards. Additionally, understanding regional seismicity aids in the implementation of early warning systems and public education efforts, ultimately saving lives, and minimizing economic losses during earthquakes [40]. Therefore, it is essential to comprehend the seismicity characteristics of a region to ensure the safety and resilience of populations living in earthquake-prone areas [41]. To gain insights into the seismic activity within the region, the Probabilistic Seismic Hazard Analysis (PSHA) embarked on a comprehensive assessment [42]. A circular study area spanning 500 km in radius was chosen for this purpose [43-44]. The seismicity data spanning an extensive timeframe of 220 years, from 1801 to 2021, was meticulously gathered from multiple reputable sources like IMD, USGS, and etc., [45-46].

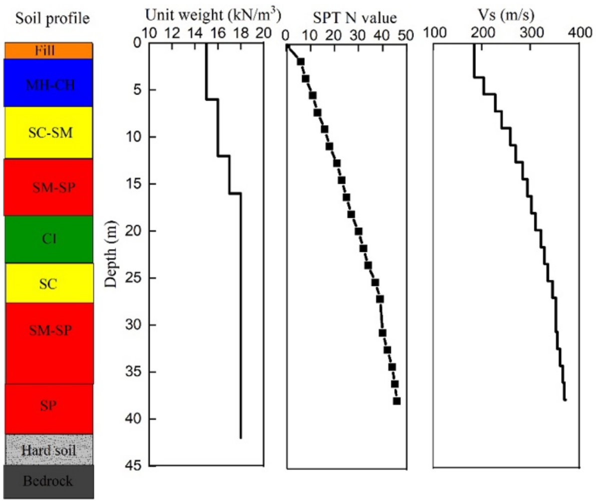


Fig. 6. Soil profile with shear wave velocity, and SPT-N variation

To create a consistent earthquake catalogue, we employed widely accepted global empirical relationships that relate various magnitudes to moment magnitude. This effort culminated in the creation of a homogeneous earthquake catalogue, encompassing a total of 386 seismic events, each registering a magnitude greater than 3.0 M_w [47]. The subsequent step involved identifying distinct seismic sources within our designated study area. This task was accomplished by referring to the geoscientific publications known as the "Seismotectonic Atlas of India and Adjoining Areas," issued by the Geological Survey of India. In total, 47 seismic sources were pinpointed within the study area, with 38 being categorized as faults and the remainder as lineaments and shear zones [48]. These identified seismic sources played a pivotal role in the estimation of maximum expected magnitude (M_{max}) and in the subsequent seismic hazard analysis [49]. To ensure the integrity of our earthquake catalogue, a thorough completeness analysis was conducted using the [50-51] methods, a critical aspect of the assessment process. The catalogue was divided into six distinct groups, each characterized by a constant Δm of 0.5 M_w. The completeness of magnitude within each group was meticulously determined, and the essential hazard parameters required for conducting the SHA were computed using recurrence relations via the least square method [52]. In addition to these methods, the seismic hazard parameters were also estimated utilizing the maximum likelihood method and a statistical approach as proposed by Kijko [53]. These calculated hazard parameters serve as the cornerstone of our PSHA, forming the bedrock upon which our seismic risk assessments and mitigation strategies are built [54-56]. The seismotectonic map of the Amaravati region is depicted in figure 7, while figure 8 presents a histogram illustrating the frequency of earthquakes based on their distance ranges: < 100 km, 100 to 300 km, and > 300 km.

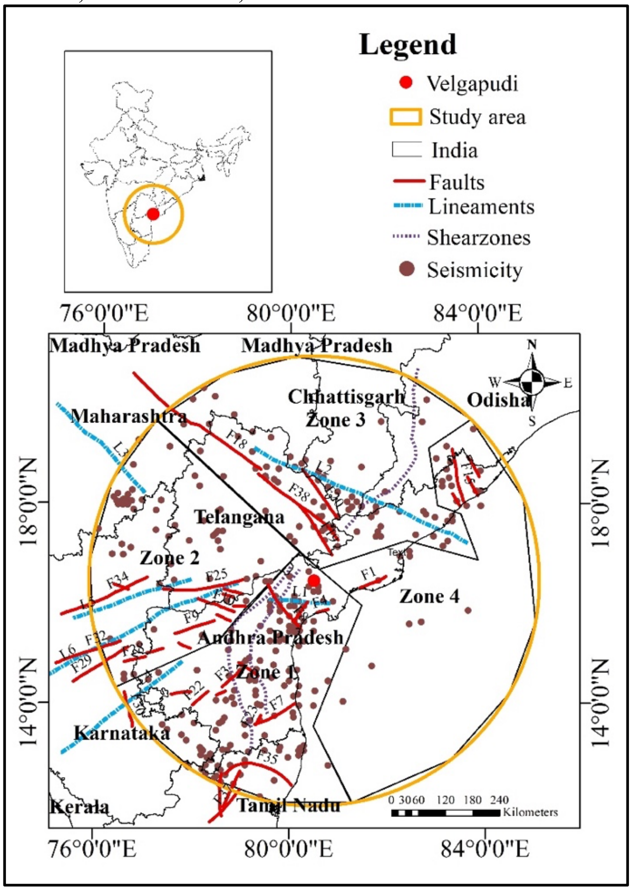


Fig. 7. Seismotectonic map of the Amaravati region

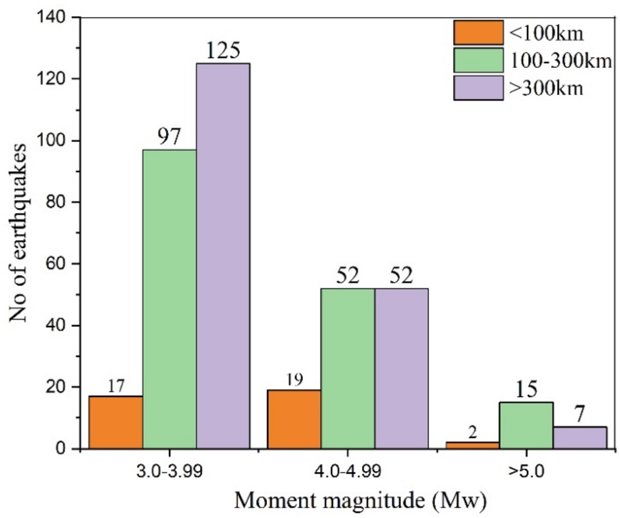


Fig. 8. Earthquake Frequency by Distance Range

2.3 Seismic hazard computation

Seismic hazard computation and analysis are critically important for assessing and mitigating earthquake risks in earthquake-prone regions. By analyzing historical seismic data, geological conditions, and fault line information, scientists can predict the likelihood and potential impact of future earthquakes [56]. This information is invaluable for urban planning, engineering design, and disaster preparedness, enabling communities to build resilient infrastructure, implement safety measures, and save lives during the seismic event [54-56]. Additionally, it aids in insurance pricing and risk management, making it a fundamental tool for both public safety and economic stability in earthquake-prone areas [28].

The SHA for the Amaravati region was carried out using Cornell's [6] methodology with the assistance of the R-CRISIS software [20]. The study area was divided into different grids of, each measuring 0.2º × 0.2º, and the hazard intensity was calculated at each grid point using ground motion prediction equation relationships recommended by the NDMA [19]. Following the successful computation of the hazard, hazard intensity values were determined for return periods of 475, 975, and 2475 years, corresponding to probabilities of exceedance (PoE) of 10%, 5%, and 2% over a 50-year period. Two approaches were used to estimate hazard intensity: the first approach utilized a complete earthquake catalogue as input, while the second approach computed hazard intensity for each seismic source zone (SSZ). The previously determined hazard parameters were employed as input data for both scenarios. The input hazard parameters were evaluated in two scenarios: in the first scenario, the entire earthquake catalogue was considered, whereas in the second scenario, the catalogue data was considered based on the relevant SSZ [28]. The results revealed that hazard values estimated on a zone-by-zone basis tended to be slightly higher than those from the zone-less scenario. Consequently, the higher hazard values were selectively utilized in the response analysis. The range of hazard intensities at the rock level varied, with values of 0.067 g, 0.092 g, and 0.136 g for return periods of 475, 975, and 2475 years, respectively, corresponding to PoE over a 50-year period. A uniform hazard response spectrum (UHRS) was developed based on the obtained spectral accelerations for return periods of 475, 975, and 2475 years [28]. This UHRS was then compared with the spectrum provided by BIS for maximum considered earthquake and design basis earthquake values [3]. The spatial distribution of peak acceleration corresponding to different return periods relative to the bedrock level is depicted in figure 9, while figure 10 illustrates the cumulative seismic hazard curves of the Amaravati region, Andhra Pradesh.

2.4 Ground Response Analysis

Ground response analysis is crucial for assessing the seismic vulnerability of a region. By analyzing how the ground behaves during an earthquake, engineers and seismologists can determine the potential impact on structures and infrastructure [24]. This information is vital for designing earthquake-resistant buildings and infrastructure, ensuring public safety, and minimizing economic losses. Ground response analysis helps identify soil amplification effects, liquefaction potential, and other seismic hazards that can vary from one location to another. Understanding these factors enables informed decision-making in urban planning, construction, and disaster preparedness, ultimately reducing the risk of catastrophic damage and loss of life during seismic events [33]. During an earthquake, the strain energy that has built up is released in the form of seismic waves. These waves travel in all directions, passing through different types of rock formations and soil layers until they reach the surface. The characteristics of the material the waves travel through affect their intensity. The local soil conditions also modify the strong ground motion, including amplification, frequency, and duration. In this study, we aimed to estimate various response parameters at the surface of the site. To achieve this, we conducted a 1D - GRA using the DEEPSOIL v7 software [12] and an equivalent linear approach. We used actual intraplate input acceleration time histories for the analysis, scaling the input motion to a required g-value of 0.067 g. Before using the scaled input motion for the analysis, we applied a base correction. Figure 11 displays the acceleration versus time history of an input motion [27].

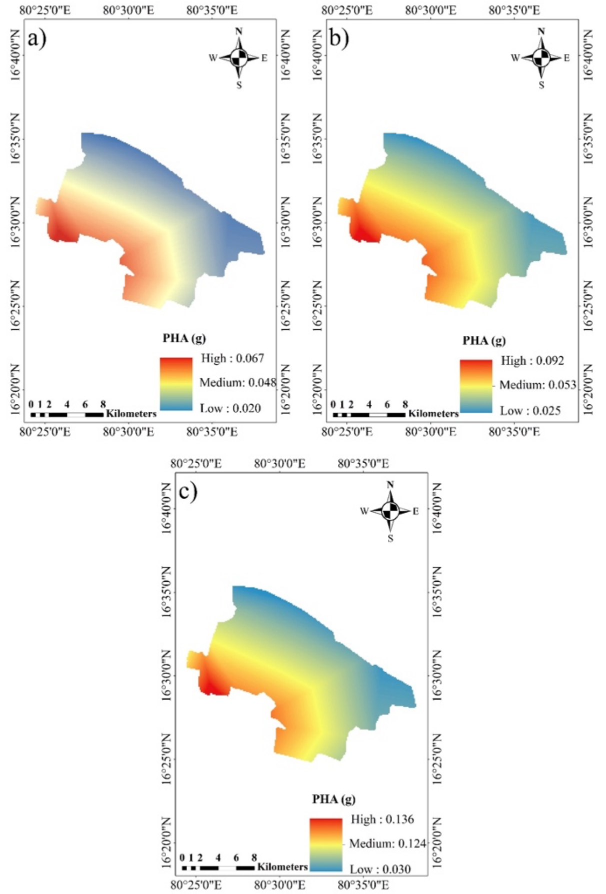


Fig. 9. Spatial distribution of peak acceleration for various return periods relative to bedrock level

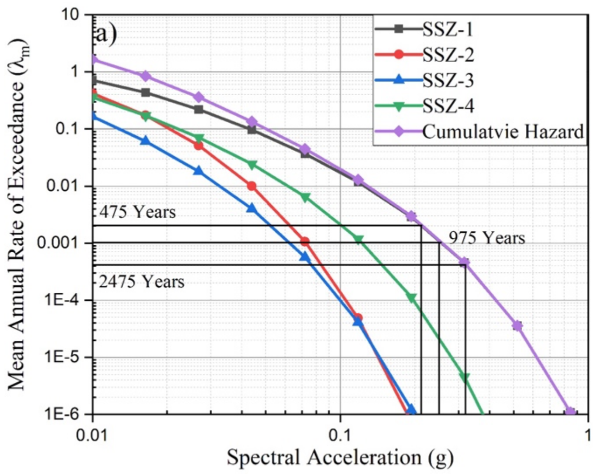


Fig. 10. Cumulative seismic hazard curves

The response of soil deposits depends on the ground motion type, the geometry and material properties of the soil layers above the bedrock. To compute the response analysis, we considered various input data including soil layer thickness, soil type, depth of the water table, Vs_{30} values for each layer, appropriate G/G_{max} curves, and damping ratio curves. We have graphically represented the response parameters obtained from nine sites at the surface level. Using GIS software, we have developed spatial distribution maps to visualize the response parameters over the area. Based on our estimates, the maximum acceleration at the surface ranged from 0.15 g to 0.23 g, with ground acceleration amplified approximately 2.31 to 3.44 times compared to the bedrock motion. In some locations, higher accelerations were observed, which may be attributed to the selected ground motion's frequency coinciding with the fundamental frequency of the soil column [39]. The amplification factor was used to measure the potential amplification at the soil column, ranging from 2.43 to 3.6 at the surface level, with the PGA ranging from 0.16 g to 0.24 g. Higher amplification factor values were associated with filled-up soils, silty sand deposits, and shallow water table depths. Our study's results have been compared with similar studies, and based on our findings, the following conclusions are highlighted.

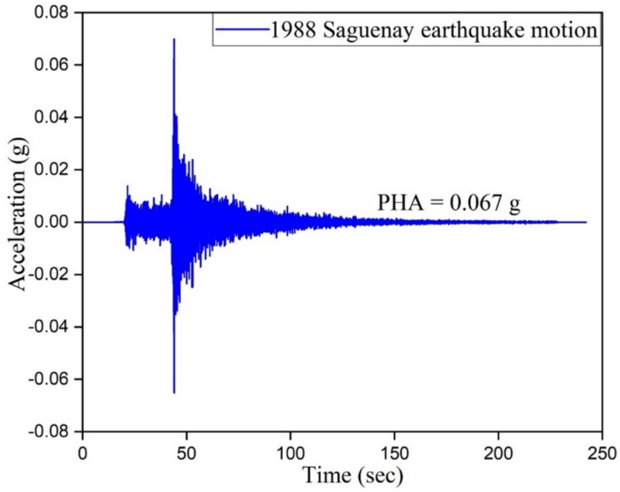


Fig. 11. Illustrates the acceleration vs. time history of input motion.

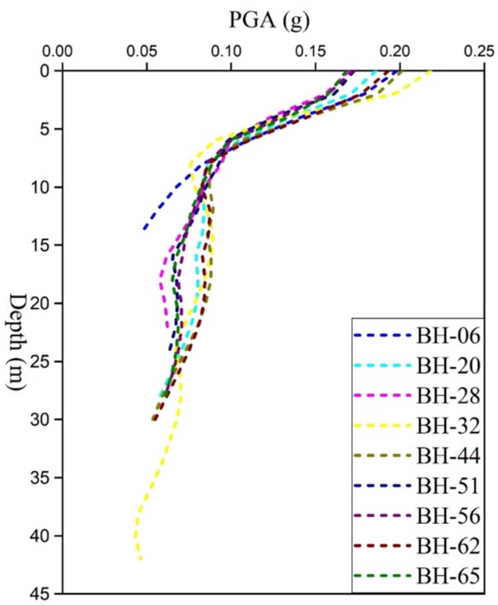


Fig. 12. Variation in PGA with Depth

The following thematic maps depict the results of the study, illustrating the variations of PGA with depth (figure 12), Spectral acceleration with spectral period (figure 13), the spatial distribution of amplification factor (figure 14), rock depth variations (figure 15), and the spatial distribution of PGA at the surface level (figure 16). In Figure 12, we observe the variations of PGA with depth, shedding light on how this parameter changes at different depths within the study area. In Figure 13, we delve into the relationship between Spectral acceleration and spectral period, which helps us understand the seismic behaviour of the area across different frequency ranges. Figure 14 presents the spatial distribution of the amplification factor, aiding in the identification of regions with significant amplification or attenuation effects. Figure 15 focuses on depth variations, allowing us to analyse how certain geological features may impact seismic activity at different depths. Lastly, in figure 16, we examine the spatial distribution of PGA at the surface level, providing critical data for assessing potential seismic hazards in the study area [40].

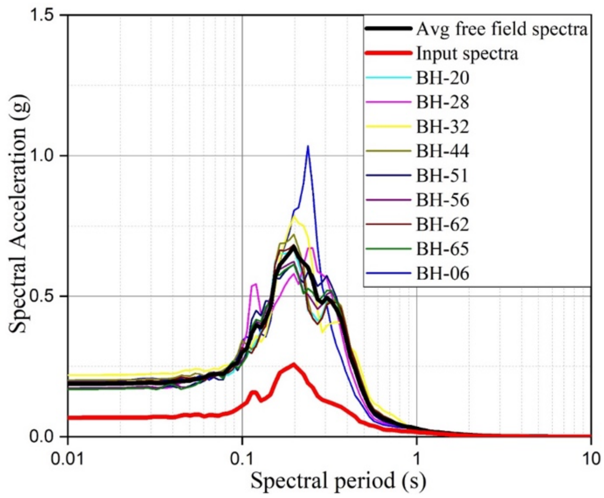


Fig. 13. Spectral Acceleration vs. Spectral Period

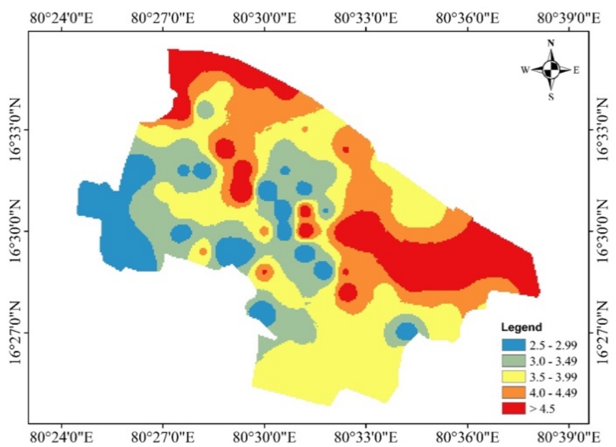


Fig. 14. Spatial distribution of amplification factor

2.5 Liquefaction susceptibility analysis

Analyzing liquefaction susceptibility in any region is crucial for several reasons. Firstly, it helps assess the potential risk of soil liquefaction during seismic events, which can lead to significant damage to infrastructure, posing a threat to public safety. Secondly, it informs urban planning and building code regulations, ensuring that construction practices are adapted to the local geological conditions [43]. Additionally, understanding liquefaction susceptibility aids in disaster preparedness and response, allowing authorities to allocate resources effectively and implement mitigation measures. Overall, this analysis plays a pivotal role in minimizing the impact of earthquakes on communities, infrastructure, and the environment, ultimately saving lives and reducing economic losses [10].

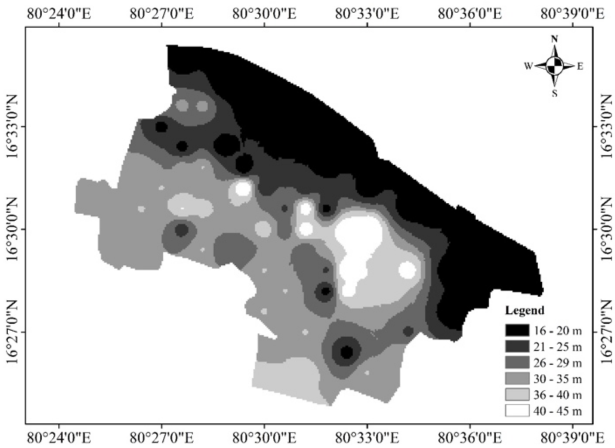


Fig. 15. Depth-Related Variations

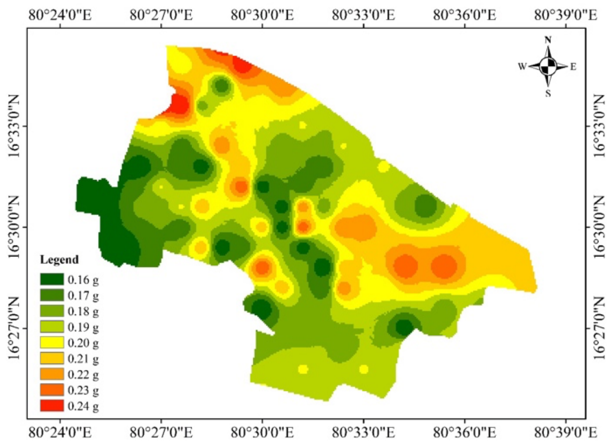


Fig. 16. Spatial distribution of PGA at the surface level

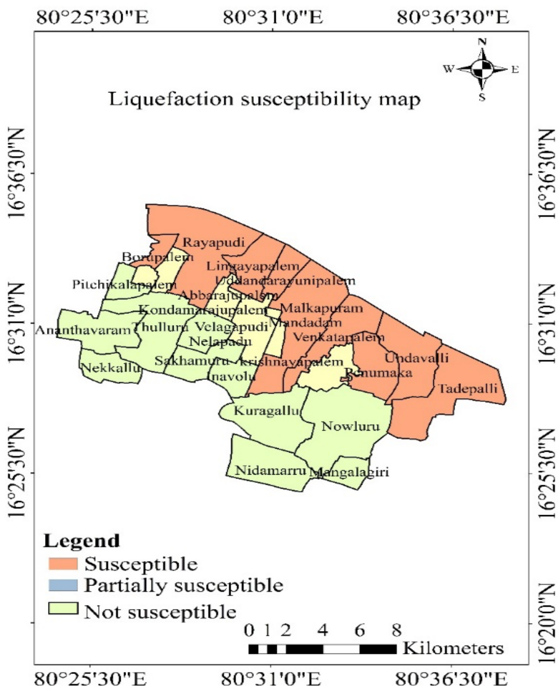


Fig. 17. Liquefaction Susceptibility Map of the Amaravati Region

Researchers worldwide concurred that clayey soils could be susceptible to liquefaction if they adhered to the multiple criteria. In this research, we assessed the liquefaction susceptibility of the Amaravati region by incorporating criteria and principles from a prior study [44]. After analyzing the obtained data, we categorized the study area into three distinct groups: susceptible, partially susceptible, and non-susceptible. Figure 17 visually represents the liquefaction susceptibility map of the Amaravati region.

3. Conclusions and limitations of the investigation

In this comprehensive study of the Amaravati region in Andhra Pradesh, we have conducted a thorough investigation spanning seismological, geological, geomorphological, and geotechnical dimensions. Our findings reveal a diverse range of geological formations, from the Archean to Recent periods, and characterize Amaravati as a shallow-depth area with weathered rock extending up to 45 meters below the surface. Seismic site classification places the region in Class 'D' (Vs30 = 180 m/s to 360 m/s) according to NEHRP and Class 'C' (Vs30= 180 m/s to 360 m/s) per the EC-08 standards. A careful review of historical earthquake distribution patterns indicates relatively low seismicity in Amaravati. Seismic hazard parameters were estimated, yielding an a-value of 3.55 and a b-value of 0.85. While the b-value aligns with those of other Peninsular Indian cities, our findings do not suggest frequent seismic activity in this area. Subzone-based analysis revealed that SSZ-2 bears the greatest seismic hazard, with the highest estimated Mmax. PSHA yielded values of 0.0136 g for maximum considered earthquake and 0.067 g for design basis earthquake, slightly elevated compared to BIS standards. Uniform hazard response spectra were developed for return periods of 475, 975, and 2475 years. Site response analysis at 65 locations revealed PGA ranging from 0.16 g to 0.24 g at the surface, with an amplification factor range of 2.43 - 3.6. The region tends to amplify ground motion by approximately 3.44 times compared to bedrock motion. Liquefaction risk assessment considered multiple factors, aiding disaster preparedness and response. These findings provide valuable insights into the seismic characteristics of Amaravati, informing future seismic risk assessments and mitigation strategies.

Despite the study's contributions, several limitations were identified. The geotechnical investigation relied on a limited number of borehole locations (65), potentially affecting the accuracy of soil classification and water table variations, which could influence response spectra. An empirical relation was used to estimate V_s profiles, introducing potential inaccuracies compared to direct measurements. Seismic source data from a 2000 publication may have missed recent seismic activity details, and attenuation data was based on specific GMPE, suggesting variability with other models. Additionally, ground response parameters were derived from intraplate region data due to a lack of localized records for Amaravati, impacting the study's seismic hazard assessment. These limitations underscore the need for further refinement and validation to enhance the reliability and specificity of future studies in the region.

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